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ANALYSIS OF COLLISIONAL ORIENTATION AND ALIGNMENT STUDIES USING SPIN-POLARIZED ELECTRONS AND LASER EXCITED ATOMS

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We have developed a general framework using density matrices for the analysis of atomic excitation by spin-polarized electrons. This framework is applied to the specific case of the $3S_{1/2} \rightarrow 3P_{3/2}$ transition in Na, as studied by the time-reversed, superelastic scattering process. The scattering is characterized in terms of physical parameters describing the collisionally excited P-state, i.e., its angular momentum ($L_\perp$), linear polarization (P_{lin}), and alignment angle (τ), with these parameters defined separately for singlet and triplet excitation. We derive a general expression for the scattering intensity which is valid for arbitrary electron polarization and atomic state preparation.

We begin with the general expression describing the scattering intensity in an experiment with initial state preparation but no final state selection,

$$I = C\, Tr\, (\sigma^{prep} F^{\dagger} F) = C\, Tr\, (\sigma^{prep} \rho)$$

where the constant C contains all purely experimental factors such as target and projectile densities, detection efficiencies, flux factors, etc. Preparation of the initial state is described by the density matrix σ^{prep}. The elements of the transition matrix F are the complex scattering amplitudes, in some appropriately chosen representation, describing collisionally-induced transitions between any initial and any final state.

The initial state density matrix, σ^{prep}, must describe both the initial electron spin-polarization and the optical state preparation of the atom. It thus can be expressed as the outer product of separate density matrices describing the incident electrons and incident atoms. The incident electron spin-polarization is completely described by its components, P_x, P_y and P_z, along the three coordinate axes.

The density matrix, σ^{atom} describing the initial P-state of the atom can be decomposed into separate descriptions of its spin and orbital angular momentum. We write the atomic state preparation density matrix as

$$\sigma^{atom} = \frac{1}{2} \begin{bmatrix} (\sigma_0 + \sigma_z) & (\sigma_x + i\sigma_y) \\ (\sigma_x + i\sigma_y) & (\sigma_0 + \sigma_z) \end{bmatrix}$$

where σ_0, σ_x, σ_y and σ_z are each 3 × 3 submatrices with rows and columns labeled by $M_L = \pm 1, 0$. These submatrices describe the orbital angular momentum properties of unpolarized atoms or atoms polarized along the three coordinate axes, respectively. The matrix elements can be expressed for any general optical pumping configuration in terms of optical pumping parameters in the photon frame.[1]

The scattering matrix ρ is simplified by decomposition into the separate singlet and triplet contributions to the scattering which are described by the scattering submatrices s and t. These 3 × 3 sub-matrices have rows and columns labeled by $\Delta M_L = \pm 1, 0$ and can be expressed in terms of a singlet and triplet $L_\perp$, P_{lin} and τ. Because spin is conserved in this collision, the matrix ρ is a diagonal 4 × 4 matrix with rows and columns labeled by the 4 relative orientations of electron and atom spins. The diagonal elements are the submatrices t, t, t and s.

Using these definitions the scattering intensity is written in the form

$$I = \frac{C}{4} \Big[Tr\,[\sigma_0(3t + s)] + P_x\, Tr\,[\sigma_x(t - s)] + P_y\, Tr\,[\sigma_y(t - s)] + P_z\, Tr\,[\sigma_z(t - s)] \Big].$$

This form of the scattering intensity makes very clear the relationships between experimental geometries and the basic information available from such experiments. Specific experimental examples will be discussed with a view toward complete determination of the relevant scattering amplitudes and phases.

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1. A. Fischer and I. V. Hertel, Z. Phys. A 304, 103 (1982).